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Gas-Insulated Transmission Line (GIL)

18.1	Introduction	18-1
18.2	History	18-2
18.3	System Design.....	18-3
	Technical Data • Standard Units • Laying Methods	
18.4	Development and Prototypes.....	18-9
	Gas Mixture • Type Tests • Long-Duration Tests	
18.5	Advantages of GIL.....	18-21
	Safety and Gas Handling • Magnetic Fields	
18.6	Application of Second-Generation GIL	18-25
18.7	Quality Control and Diagnostic Tools	18-27
18.8	Corrosion Protection	18-28
	Passive Corrosion Protection • Active Corrosion Protection	
18.9	Voltage Stress Coming from the Electric Power Net.....	18-30
	Overvoltage Stresses • Maximum Stresses by Lightning Strokes • Modes of Operation • Application of External and Integrated Surge Arresters • Results of Calculations • Insulation Coordination	
18.10	Future Needs of High-Power Interconnections.....	18-32
	Metropolitan Areas • Use of Traffic Tunnels	
	References.....	18-35

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18.1 Introduction

The gas-insulated transmission line (GIL) is a system for the transmission of electricity at high power ratings over long distances. In cases where overhead lines are not possible, the GIL is a viable technical solution to bring the power transmitted by an overhead line underground without a reduction of power transmission capacity.

As a gas-insulated system, the GIL has the advantage of electrical behavior similar to that of an overhead line, which is important to the operation of the complete network. Because of the large cross section of the conductor, the GIL has low electrical losses compared with other transmission systems (overhead lines and cables). This reduces the operating and transmission costs, and it contributes to reduction of global warming because less power needs to be generated.

Safety of personnel in the vicinity of a GIL is very high because the solid metallic enclosure provides reliable protection. Even in the rare case of an internal failure, the metallic enclosure is strong enough to withstand damage. This allows the use of GILs in street and railway tunnels and under bridges with public traffic. No flammable materials are used to build a GIL. The use of GILs in traffic tunnels makes the tunnels more economical and can solve some environmental problems. If GIL is added to a traffic tunnel, the cost

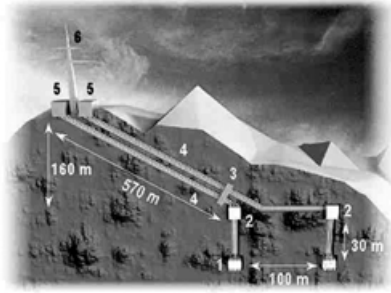


FIGURE 18.1 GIL (420 kV, 2500 A) in Schluchsee, Germany. (Courtesy of Siemens.)

can be shared between the electric power supply company and the owner of the traffic part (train, vehicles). The environmental advantage is that no additional overhead line needs to be built parallel to the tunnel. Because of the low capacitive load of the GIL, long lengths of 100 km and more can be built.

Where overhead lines are not suitable due to environmental factors or where they would spoil a particular landscape, the GIL is a viable alternative because it is invisible and does not disturb the landscape. The GIL consists of three single-phase encapsulated aluminum tubes that can be directly buried in the ground or laid in a tunnel. The outer aluminum enclosure is at ground potential. The interior, the annular space between the conductor pipe and the enclosure, is filled with a mixture of gas, mainly nitrogen (80%) with some SF_6 (20%) to provide electrical insulation. A reverse current, more than 99% of the conductor current value, is induced in the enclosure. Because of this reverse current, the outer magnetic field is very low.

GIL combines reliability with high transmission capacity, low losses, and low emission of magnetic fields. Because it is laid in the ground, GIL also satisfies the requirements for power transmission lines without any visual impact on the environment or the landscape. Of course, the system can also be used to supply power to meet the high energy demands of conurbations and their surroundings. The directly buried GIL combines the advantage of underground laying with a transmission capacity equivalent to that of an overhead power line [1–3].

18.2 History

The gas-insulated transmission line (GIL) was invented in 1974 to connect the electrical generator of a hydro pump storage plant in Schluchsee, Germany. Figure 18.1 shows the tunnel in the mountain with the 400-kV overhead line. The GIL went into service in 1975 and has remained in service without interruption since then, delivering peak energy into the southwestern 420-kV network in Germany. With 700 m of system length running through a tunnel in the mountain, this GIL is still the longest application at this voltage level in the world. Today, at high-voltage levels ranging from 135 to 550 kV, a total of more than 100 km of GILs have been installed worldwide in a variety of applications, e.g., inside high-voltage substations or power plants or in areas with severe environmental conditions.

Typical applications of GIL today include links within power plants to connect high-voltage transformers with high-voltage switchgear, links within cavern power plants to connect high-voltage transformers in the cavern with overhead lines on the outside, links to connect gas-insulated substations (GIS) with overhead lines, and service as a bus duct within gas-insulated substations. The applications are carried out under a wide range of climate conditions, from low-temperature applications in Canada, to the high ambient temperatures of Saudi Arabia or Singapore, to the severe conditions in Europe or in South Africa. The GIL transmission system is independent of environmental conditions because the high-voltage system is completely sealed inside a metallic enclosure.

The GIL technology has proved its technical reliability in more than 2500 km-years of operation without a major failure. This high system reliability is due to the simplicity of the transmission system, where only aluminum pipes for conductor and enclosure are used, and the insulating medium is a gas that resists aging.

TABLE 18.1 Technical Data for 420-kV and 550-kV GIL Transmission Networks

Type	Value
Nominal voltage (kV)	420/550
Nominal current (A)	3150/4000
Lightning impulse voltage (kV)	1425/1600
Switching impulse voltage (kV)	1050/1200
Power frequency voltage (kV)	630/750
Rated short-time current (kA/3 s)	63
Rated gas pressure (bar)	7
Insulating gas mixture	80% N ₂ , 20% SF ₆

Source: Courtesy of Siemens.

The high cost of GILs has restricted their use to special applications. However, with the second-generation GIL, a total cost reduction of 50% has made the GIL economical enough for application over long distances. The breakthrough in cost reduction is achieved by using highly standardized GIL units combined with the efficiencies of automated orbital-welding machines and modern pipeline laying methods. This considerably reduces the time required to lay the GIL, and angle units can be avoided by using the elastic bending of the aluminum pipes to follow the contours of the landscape or the tunnel. This breakthrough in cost and the use of N₂/SF₆ gas mixtures have made possible what is now called second-generation GIL, and it is a very interesting transmission system for high-power transmission over long distances, especially if high power ratings are needed.

The second-generation GIL was first built for eos (energie ouest suisse) at the PALEXPO exhibition area, close to the Geneva Airport in Switzerland. Since January 2001, this GIL has been in operation as part of the overhead line connecting France with Switzerland. The success of this project has demonstrated that the new laying techniques are suitable for building very long GIL transmission links of 100 kilometers or more within an acceptable time schedule.

18.3 System Design

18.3.1 Technical Data

The main technical data of the GIL for 420-kV and 550-kV transmission networks are shown in Table 18.1. For 550-kV applications, the SF₆ content or the diameter of the enclosure pipe might be increased.

The rated values shown in Table 18.1 are chosen to match the requirements of the high-voltage transmission grid of overhead lines. The power transmission capacity of the GIL is 2000 MVA whether tunnel laid or directly buried. This allows the GIL to continue with the maximum power of 2000 MVA of an overhead line and bring it underground without any reduction in power transmission [4, 5]. The values are in accordance with the relevant IEC standard for GILs, IEC 61640 [6].

18.3.2 Standard Units

Figure 18.2 shows a straight unit combined with an angle unit. The straight unit consists of a single-phase enclosure made of aluminum alloy. In the enclosure (1), the inner conductor (2) is fixed by a conical insulator (4) and lays on support insulators (5). The thermal expansion of the conductor toward the enclosure is adjusted by the sliding contact system (3a, 3b). One straight unit has a length up to 120 m made by single pipe sections welded together by orbital-welding machines. If a directional change exceeds what the elastic bending allows, then an angle element (shown in Figure 18.2) is added by orbital welding with the straight unit. The angle element covers angles from 4 to 90°. Under normal conditions of the landscape, no angle units are needed because the elastic bending, with a bending radius of 400 m, is sufficient to follow the contour.

At distances of 1200 to 1500 m, disconnecting units are placed in underground shafts. Disconnecting units are used to separate gas compartments and to connect high-voltage testing equipment for the

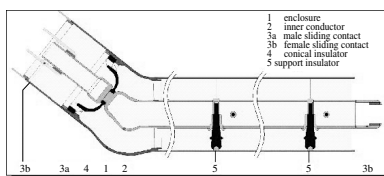


FIGURE 18.2 Straight construction unit with an angle element. (Courtesy of Siemens.)

commissioning of the GIL. The compensator unit is used to accommodate the thermal expansion of the enclosure in sections that are not buried in the earth. A compensator is a type of metallic enclosure, a mechanical soft section, which allows movement related to the thermal expansion of the enclosure. It compensates the length of thermal expansion of the enclosure section. Thus compensators are used in tunnel-laid GILs as well as in the shafts of directly buried GILs.

The enclosure of the directly buried GIL is coated in the factory with a multilayer polymer sheath as a passive protection against corrosion. After completion of the orbital weld, a final covering for corrosion protection is applied on site to the joint area.

Because the GIL is an electrically closed system, no lightning impulse voltage can strike the GIL directly. Therefore, it is possible to reduce the lightning impulse voltage level by using surge arresters at the end of the GIL. The integrated surge-arrester concept allows reduction of high-frequency overvoltages by connecting the surge arresters to the GIL in the gas compartment [7].

For monitoring and control of the GIL, secondary equipment is installed to measure gas pressure and temperature. These are the same elements that are used in gas-insulated switchgear (GIS). For commissioning, partial-discharge measurements are obtained using the sensitive very high frequency (VHF) measuring method.

An electrical measurement system to detect arc location is implemented at the ends of the GIL. Electrical signals are measured and, in the very unlikely case of an internal fault, the position can be calculated by the arc location system (ALS) with an accuracy of 25 m.

The third component is the compensator, installed at the enclosure. In the tunnel-laid version or in an underground shaft, the enclosure of the GIL is not fixed, so it will expand in response to thermal heat-up during operation. The thermal expansion of the enclosure is compensated by the compensation unit. If the GIL is directly buried in the soil, the compensation unit is not needed because of the weight of the soil and the friction of the surface of the GIL enclosure.

The fourth and last basic module used is the disconnecting unit, which is used every 1.2 to 1.5 km to separate the GIL in gas compartments. The disconnecting unit is also used to carry out sectional high-voltage commissioning testing.

An assembly of all these elements as a typical setup is shown in [Figure 18.3](#), which illustrates a section of a GIL between two shafts (1). The underground shafts house the disconnecting and compensator units (2). The distance between the shafts is between 1200 and 1500 m and represents one single gas compartment. A directly buried angle unit (3) is shown as an example in the middle of the figure. Each angle unit also has a fix point, where the conductor is fixed toward the enclosure.

18.3.3 Laying Methods

The GIL can be laid aboveground on structures, in a tunnel, or directly buried into the soil like an oil or gas pipeline. The overall costs for the directly buried version of the GIL is, in most cases, the least expensive version of GIL laying. For this laying method, sufficient space is required to provide accessibility for working on site. Consequently, directly buried laying will generally be used in open landscape crossing the countryside, similar to overhead lines, but invisible.

18.3.3.1 Directly Buried

The most economical and fastest method of laying cross country is the directly buried GIL. Similar to pipeline laying, the GIL is continuously laid within an open trench. A nearby preassembly site reduces

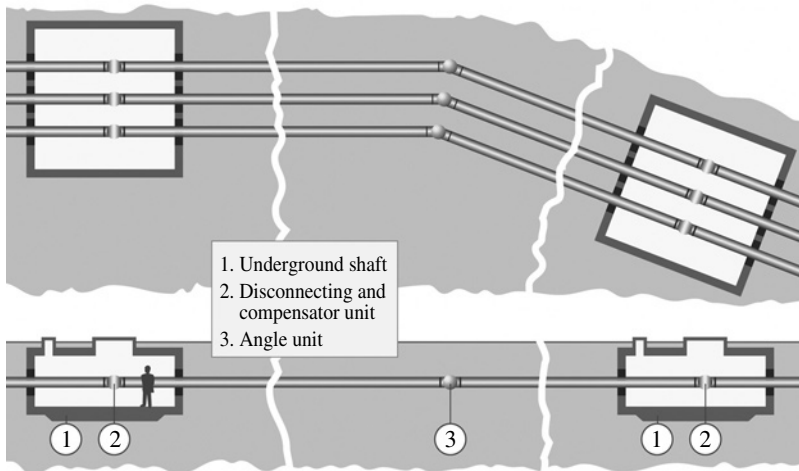


FIGURE 18.3 Directly buried GIL system components. (Courtesy of Siemens.)

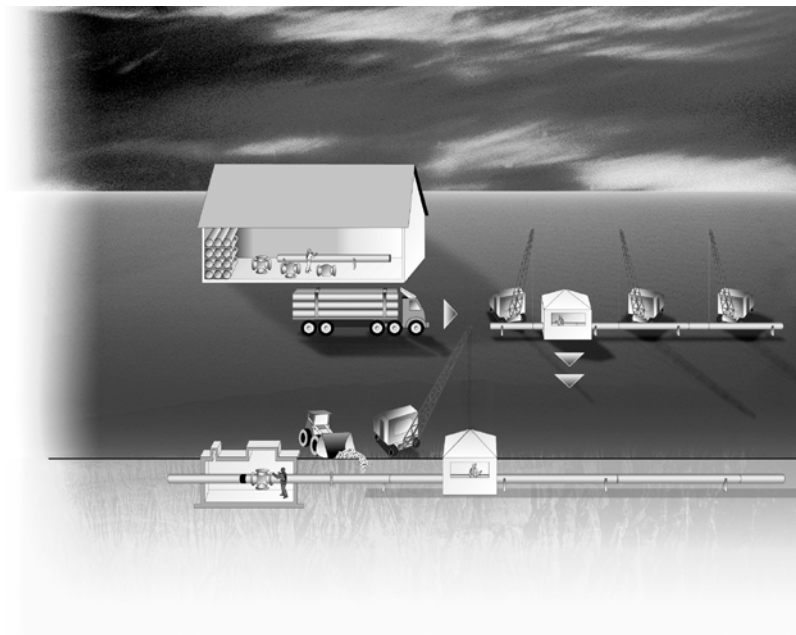


FIGURE 18.4 Laying procedure for a directly buried GIL. (Courtesy of Siemens.)

the cost of transporting GIL units to the site. With the elastic bending of the metallic enclosure, the GIL can flexibly adapt to the contours of the landscape. In the soil, the GIL is continuously anchored, so that no additional compensation elements are needed [8, 9].

The laying procedure for a directly buried GIL is shown in Figure 18.4. The left side of the figure shows a digging machine opening the trench, which will have a depth of about 1.2 to 2 m. The building shown close to the trench is the prefabrication area, where GIL units of up to 120 m in length are preassembled and prepared for laying. The GIL units are transported by cranes close to the trench and then laid into the trench. The connection to the already laid section is done within a clean housing tent in the trench. The clean housing tent is then moved to the next joint and the trench is backfilled. [Figure 18.5](#) shows the moment of laying the GIL into the trench. [Figure 18.6](#) shows the bended tube and backfilling of the trench.



FIGURE 18.5 Laying the GIL into the soil. (Courtesy of Siemens.)

18.3.3.2 Aboveground Installation

Aboveground GIL installations are usually installed on steel structures in heights of 1 to 5 m above-ground. The enclosures are supported in distances of 20 to 40 m. This is because of the rigid metal enclosure. Because of the mechanical layout of the GIL, it is also suitable to use existing bridges to cross, e.g., a river.

The aboveground installations are typical for installations within substations to connect, e.g., the bay of a GIS with an overhead line, where larger distances between the phases of the three-phase system are used, or to connect the GIS directly with the step-down transformer. The GIL is often chosen if very high reliability is needed, e.g., in nuclear power stations.

Another reason for GIL applications in substation power is that the aboveground installations are used for the transmission of very high electrical power ratings. The strongest GIL has been installed in Canada



FIGURE 18.6 Bended tube and backfilling. (Courtesy of Siemens.)

at the Kensington Nuclear Power Station in a substation with GIS where single sections of the GIL bus bar system can carry currents of 8000 A and can withstand short circuit currents of 100,000 A.

Aboveground GIL installations inside substations are widely used in conjunction with GIS. Usually, the substations are fenced and, therefore, not accessible to the public. If this is not the case, laid tunnel or directly buried GIL will be chosen for safety reasons. Accessibility of GIL to the public is generally avoided so as not to allow manipulations on the GIL (e.g., drilling a hole into the enclosure), which can be dangerous because of the high voltage potential inside.

18.3.3.3 Tunnel-Laid

If there is not enough space available to bury a GIL, laying the GIL into a tunnel will be the most appropriate method. This tunnel-laying method is used in cities or metropolitan areas as well as when crossing a river or interconnecting islands. Because of the high degree of safety that GIL offers, it is possible to run a GIL through existing or newly built street or railway tunnels, for example in the mountains.

Modern tunneling techniques have been developed during the past few years with improvements in drilling speed and accuracy. So-called microtunnels, with a diameter of about 3 m, are economical solutions in cases when directly buried GIL is not possible, e.g., in urban areas, in mountain crossings, or in connecting islands under the sea. Such microtunnels are usually the shortest connection between two points and, therefore, reduce the cost of transmission systems. After commissioning, the system is easily accessible. Figure 18.7 shows a view into a GIL tunnel at the IPH test field in Berlin. This tunnel of 3 m in diameter can accommodate two systems of GIL for rated voltages of up to 420/550 kV and with rated currents of 3150 A. This translates to a power transmission capacity of 2250 MVA for each system.

Figure 18.8 shows a view into the tunnel at PALEXPO at Geneva Airport in Switzerland with two GIL systems. The tunnel dimensions in this case are 2.4 m wide and 2.6 m high. The transmission capacity of this GIL is also 2250 MVA at 420/550-kV rated voltage with rated currents up to 3150 A.

In both laying methods — directly buried and tunnel laid — the elastic bending of the GIL can be seen in Figure 18.6 and Figure 18.8, respectively. The minimum acceptable bending radius is 400 m.

Figure 18.9 shows the principle for the laying procedure in a tunnel. GIL units of 11 to 14 m in length are brought into a tunnel by access shafts and then connected to the GIL transmission line in the tunnel. In cases with horizontal accessibility — such as in a traffic tunnel for trains or vehicles — the GIL units can be much longer, 20 to 30 m by train transportation. This increase in length reduces the assembly work and time and allows major cost reductions. A special working place for mounting and welding is installed at the assembly site [10]. As seen in Figure 18.9, the delivery and supply of prefabricated elements (1) is brought to the shaft or tunnel entrance. After the GIL elements are brought into the shaft to the mounting and welding area (2), the elements are joined by an orbital-welding machine. The GIL section is then brought into the tunnel (3). When a section is ready, a high-voltage test is carried out (4) to validate each section.



FIGURE 18.7 View into the tunnel. (Courtesy of Siemens.)



FIGURE 18.8 Tunnel-laid GIL for voltages up to 550 kV. (Courtesy of Siemens.)

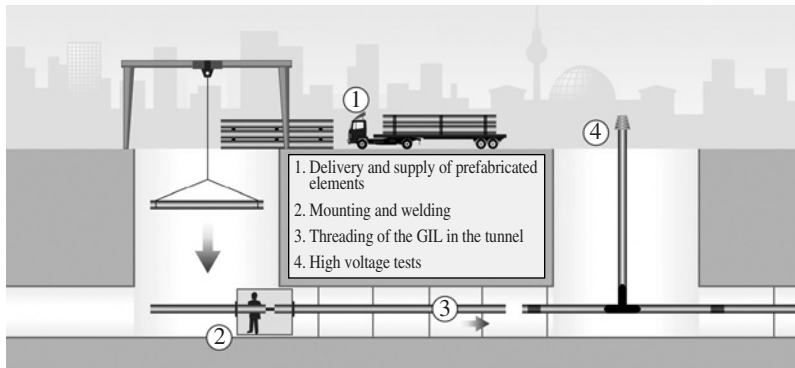


FIGURE 18.9 Laying and testing in a tunnel. (Courtesy of Siemens.)

TABLE 18.2 Technical Data for Tunnel-Laid and Directly Buried GIL Transmission Networks

	Tunnel-Laid GIL		Directly Buried GIL	
Nominal voltage (kV)	420/550	kV	420/550	kV
Nominal current (A)	3150	A	3150	A
Lightning impulse voltage (kV)	1425	kV	1425	kV
Switching impulse voltage (kV)	1050	kV	1050	kV
Rated short-time current (kA/3 s)	63	kA/3 s	63	kA/3 s
Rated transmission capacity (MVA)	2250	MVA	2250	MVA
Insulating gas mixture	80% N ₂	N ₂	80% N ₂	N ₂
	20% SF ₆	SF ₆	20% SF ₆	SF ₆
Pipe outside dimension (mm)	520	mm	600	mm

Source: Courtesy of Siemens.

18.4 Development and Prototypes

Development of the second-generation GIL was based on the knowledge of gas-insulated technologies and was carried out in type tests and long-duration tests. The type tests proved the design in accordance with IEC 60694, IEC 60517, IEC 61640, and related standards [11, 12]. An expected lifetime of 50 years has been simulated in long-term duration tests involving combined stresses of current and high-voltage cycles that were higher than the nominal ratings. At the IPH test laboratory in Berlin, Germany, tests have been carried out on tunnel-laid and directly buried GIL in cooperation with the leading German utilities.

A prototype tunnel-laid GIL of approximately 70-m length has been installed in a concrete tunnel. The jointing technique of a computer-controlled orbital-welding machine was applied under realistic on-site conditions. The prototype assembly procedure has also been successfully proved under realistic on-site conditions.

The directly buried gas-insulated transmission line is a further variant of GIL. After successful type tests, the properties of a 100-m-long directly buried GIL were examined in a long-duration test with typical accelerated load cycles. The results verified a service life of 50 years. Installation, construction, laying, and commissioning were all carried out under real on-site conditions. The test program represents the first successfully completed long-duration test for GIL using the insulating N₂/SF₆ gas mixture.

The technical data for the directly buried and tunnel-laid GIL are summarized in Table 18.2.

The values shown in Table 18.2 are chosen for the application of GIL in a transmission grid with overhead lines and cables. Because the GIL is an electrically closed system, meaning the outer enclosure

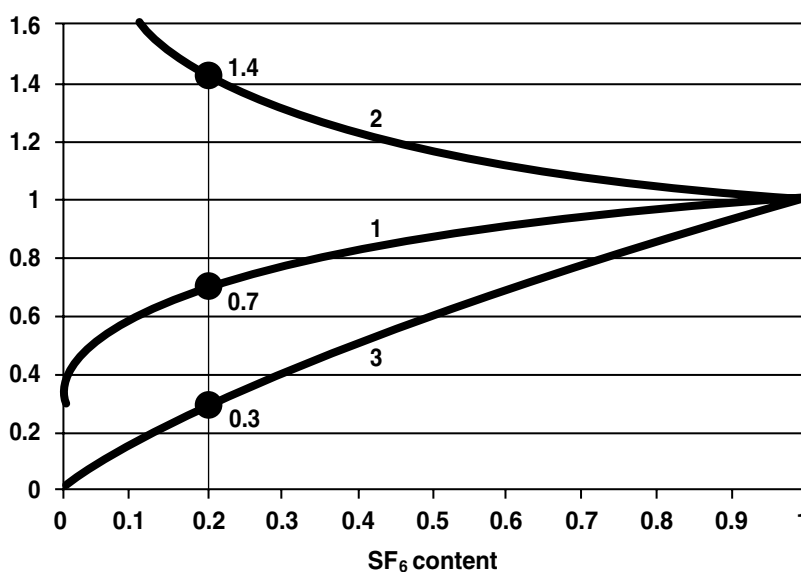


FIGURE 18.10 Normalized ideal intrinsic properties of N_2/SF_6 mixtures. 1. Pressure-reduced critical field; 2. necessary pressure for mixtures of equal critical field strength; 3. necessary amount of SF_6 for mixtures of equal critical field strength. (Courtesy of Siemens.)

is completely metallic and grounded, no lightning impulse voltage can directly strike the GIL. Therefore, it is possible to reduce the lightning impulse voltage level by using surge arresters at the ends of the GIL. The integrated surge-arrester concept allows the reduction of high-frequency overvoltages by connecting the surge arresters to the GIL in the gas compartment [7].

18.4.1 Gas Mixture

Like natural air, the gas mixture consists mainly of nitrogen (N_2), which is chemically even more inert than SF_6 . It is therefore an ideal and inexpensive admixture gas that calls for almost no additional handling work on the gas system [13]. The low percentage (20%) of SF_6 in the N_2/SF_6 gas mixture acquires high dielectric strength due to the physical properties of these two components. Figure 18.10 shows that a gas mixture with an SF_6 content of only 20% has 70% of the pressure-reduced critical field strength of pure SF_6 . The curves are defined in Figure 18.10.

A moderate pressure increase of 40% is necessary to achieve the same critical field strength of pure SF_6 .

N_2/SF_6 gas mixtures are an alternative to pure SF_6 if only dielectric insulation is needed and there is no need for arc-quenching capability, as in circuit breakers or disconnectors. Much published research work has been performed and properties ascertained in small test setups under ideal conditions [14]. The arc-quenching capability of N_2/SF_6 mixtures is inferior to pure SF_6 in approximate proportion to its SF_6 content [15]. N_2/SF_6 mixtures with a higher SF_6 concentration are successfully applied in outdoor SF_6 circuit breakers in arctic regions in order to avoid SF_6 liquefaction, but a reduced breaking capability has to be accepted.

In the event of an internal arc, the N_2/SF_6 gas mixture with a high percentage of N_2 (80%) behaves similar to air. The arc burns with a large footpoint area. Footpoint area is the area covered by the footpoint of an internal arc during the arc burning time of typically 500 ms. Consequently, the thermal-power-flow density into the enclosure at the arc footpoint is much less, which causes minimal material erosion of the enclosure. The result is that the arc will not burn through, and there is no external impact to the surroundings or the environment.



FIGURE 18.11 High-current and internal-arc test setup. (Courtesy of Siemens.)

TABLE 18.3 Parameters for Short-Circuit Withstand Test

GIL Test Parameter	Tunnel-Laid GIL	Directly buried GIL
Short-circuit peak current (kA)	185	165
Short-time current (kA)	75	63
Duration of short-circuit current (s)	0.5	3

18.4.2 Type Tests

The type tests were based on the new IEC 61640 standard [6]. The test parameters for additional tests to assess GIL lifetime performance were defined with reference to the CIGRE recommendation for prequalification tests (WG 21-03, September 1992) and IEC 61640.

For the type tests, full-scale test setups were installed, containing all essential design components.

18.4.2.1 Short-Circuit Withstand Tests

The short-circuit withstand tests were carried out on the test setup shown in Figure 18.11. The GIS test setup was assembled using the different GIS units: straight unit, angle unit, compensator unit, and disconnector unit. From left to right in Figure 18.11 there is: the straight unit; next a 90° angle unit; and at the far right a disconnection unit. Table 18.3 lists the parameters for the short-circuit withstand test. The different values for the duration of short-circuit currents are not related to design criteria but, rather, reflect regional market requirements.

After these tests, no visible damage was seen, and the functionality of the GIL prototype was not impaired. The contact resistivity was measured after the test and was well within the range of what was allowed by the IEC 61640 standard. Actually, the contact resistivity of the GIL sliding contact after the test was even a little lower than before, indicating the system's very good current-carrying capability.

18.4.2.2 Internal-Arc Test

To check whether arcing due to internal faults causes burn-through of the enclosure, an internal-arcing test was performed on the GIL prototype. Tests were carried out with arc currents of 50 and 63 kA and arc duration times of 0.33 and 0.5 s. The results of the internal-arcing tests showed only little damage, with the wall thickness of the enclosure eroding by only a few micrometers. The pressure rise was very low because of the size of the compartment of about 20 m in length. Figure 18.12, a view into the GIL after the arc fault test, shows very few distortions. The resistance to arcing damage means that the GIL can use the autoreclosure function, the same as with overhead lines.



FIGURE 18.12 View into the GIL after an arc fault of 63 kA and 0.5 s. (Courtesy of Siemens.)

Results of the internal-arc tests can be summarized as follows:

- No external influence during and after the internal-arc test was noticed.
- No burn-through of the enclosure occurred. Very low material erosion was observed on the enclosure and conductor.
- The pressure rise within the enclosures during arcing was so low that even the rupture discs did not open.
- The arc characteristic is much smoother compared with the characteristics in pure SF₆ (e.g., large arc diameter and lower arc traveling speed).
- Cast-resin insulators were not seriously affected.

All of these results speak in favor of the safe operation of the GIL. Even in the very unlikely event of an internal arc, the external environment is not affected. The results of the arc fault test also showed that in the case of a tunnel-laid GIL, there is no danger to the people traveling through the tunnel. This makes the GIL the only high-power transmission system that can be used in public traffic tunnels together with trains and street traffic.

18.4.2.3 Dielectric Tests

Dielectric type tests were carried out on the full-scale test setup in the high-voltage laboratory of Siemens in Berlin ([Figure 18.13](#)) and in the IPH test laboratory, also in Berlin. The tunnel-laid and directly buried GIL systems were tested according to the rated voltages and test voltages given in IEC Std. 61640. The gas pressure was set to 7 bar abs. Test parameters are presented in [Table 18.4](#).

The tests were applied with 15 positive and 15 negative impulses, and the power-frequency withstand-test voltage was applied for 1 min. All tests were passed.

18.4.3 Long-Duration Tests

To check the GIL system's suitability for practical use, every effort was made to implement a test setup that came close to real conditions. Therefore, the tunnel-laid GIL was assembled on site and installed in a tunnel made of concrete tubes (total length: 70 m). The directly buried GIL was laid in soil (total length: 100 m). The test parameters are given in [Table 18.5](#).



FIGURE 18.13 Test setup for high-voltage tests. (Courtesy of Siemens.)

TABLE 18.4 Parameters for Dielectric Type Tests at 7-bar Gas Pressure

GIL Test Parameters	Directly Buried and Tunnel-Laid GIL	Directly Buried GIL
Rated voltage, U_r	420 kV	550 kV
ac withstand test, 1 min	630 kV	750 kV
Lightning impulse test	1425 kV	1600 kV
Switching impulse test	1050 kV	1200 kV

Source: Courtesy of Siemens.

TABLE 18.5 Parameters of the Commissioning Test and the Recommissioning Test after Demonstration of a Repair Process

	GIL Test Parameters, Directly Buried		GIL Test Parameters, Tunnel Laid	
Commissioning	ac withstand test, 1 min	630 kV	ac withstand test, 10 s	550 kV
	with PD monitoring		ac withstand test, 1 min	504 kV
	Lightning impulse test	1300 kV	with PD monitoring	
	Switching impulse test	1050 kV	Lightning impulse test	1140 kV
Recommissioning, after demonstration of repair process	ac withstand test, 1 min	630 kV	ac withstand test, 10 s	550 kV
	with PD monitoring		ac withstand test, 1 min	504 kV
	Lightning impulse test	1300 kV	with PD monitoring	
	Switching impulse test	1050 kV	lightning impulse test	1140 kV
Final test (tunnel laid, after 2500 h) (directly buried, after 2880 h)	ac, 48 h, with PD monitoring	480 kV	ac withstand test, 10 s	550 kV
	ac withstand test, 1 min	630 kV	ac withstand test, 1 min	504 kV
	with PD monitoring		with PD monitoring	
	Lightning impulse test	1300 kV	lightning impulse test	1140 kV
	Switching impulse test	1050 kV		
	ac, 48 h, with PD monitoring	480 kV		

Source: Courtesy of Siemens.

TABLE 18.6 Load Cycles and Intermediate Tests of the Long-Duration Test

GIL Test Parameters, Tunnel Laid			GIL Test Parameters, Directly Buried		
Load cycles	Total duration	2500 h	Load cycles, time parameters change every 480 h	Total duration	2880 h
	Duration of one cycle	12 h		Duration of one cycle	12/24 h
	Number of cycles	210		Number of cycles	120/50
	Heating current, 7 h	3200 A		Heating current, 8 h	4000 A
	High voltage, 5 h	480 kV		High voltage, 4 or 16 h	480 kV
Intermediate tests, every 480 h	Switching impulse test	1050 kV	Intermediate tests, every 480 h	Lightning impulse test	1140 kV

Source: Courtesy of Siemens.

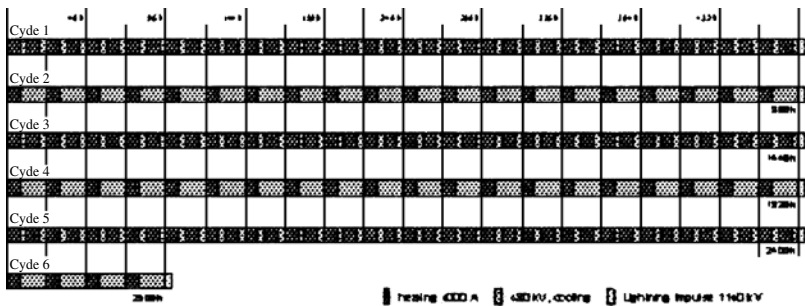


FIGURE 18.14 Long-duration test cycle of the directly buried GIL. For the tunnel-laid GIL, the test sequences of cycle type 1 had been applied for the total duration. (Courtesy of Siemens.)

The test values are derived from typical applications for directly buried and tunnel-laid GIL. The lower test voltages for the tunnel-laid GIL reflect the fact that such systems are typically used in metropolitan areas, where they are usually connected to cable systems and therefore have lower overvoltages from the net. The higher voltages for the directly buried GIL represent the typical application as part of the overhead line net, with higher overvoltages due to lightning. In any case, both applications of test voltages can be used for directly buried and tunnel-laid GIL.

The duration and cycle times of the current and high-voltage sequences were chosen to apply maximum stress to heat up and cool down the GIL system. After a heat cycle of 12 or 24 h, the current was switched off, and the high voltage was applied to the GIL at the moment when the strongest mechanical forces were coming with the cool-down phase of the GIL. The sequences are listed in Table 18.6.

The total time of the long-duration test was 2500 h, which represents a lifetime of 50 years due to the overvoltage (double value) and the mechanical stress. The complete long-duration test is shown in Figure 18.14.

GIL conductor and enclosure temperature, as well as GIL movement due to thermal expansion/contraction, were monitored during load cycles. All tests were performed successfully.

18.4.3.1 Long-Duration Test on a Tunnel-Laid GIL

A 70-m-long prototype was assembled and laid in a concrete tunnel of 3-m diameter (Figure 18.15). The arrangement contained all major components of a typical GIL, including supports for the tunnel installation. The tunnel segments are original concrete units that are laid 20 to 40 m under the street level. The technology of drilling such tunnels has improved during the past few years, and a large reduction in costs can be obtained through today's improved measuring and control techniques.

Figure 18.16 shows a top view of the long-duration test setup, which consists of a 50-m straight-construction unit, an angle unit, and another 20-m section after the directional change. The axial compensator took care of the thermal expansion of the enclosure during the load cycles. The disconnecting unit separates the GIL toward the high-voltage connection and the connection to the high-current



FIGURE 18.15 Tunnel arrangement of two systems GIL for the long-term test. (Courtesy of Siemens.)

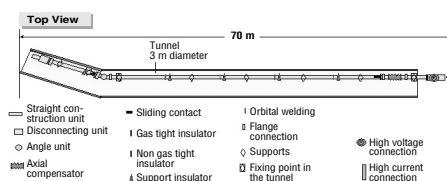


FIGURE 18.16 Arrangement of long-duration test setup. (Courtesy of Siemens.)

source. Sliding contacts inside the GIL compensate for the thermal expansion of the conductor, which slides on support insulators.

The segments of the GIL are welded with an orbital-welding machine, as seen in [Figure 18.17](#). The orbital-welding machine is highly automated and gives a high-quality, reproducible weld. Together with the orbital welding, an automated, ultrasonic measuring system provides 100% quality control of the weld, which guarantees a gas-tight enclosure with a gas leakage rate of almost zero.

In addition to the above-mentioned long-duration test with extremely high mechanical and electrical stresses, the sequence was interrupted after 960 h and a planned repair process — including the substitution of a tube length — was carried out ([Figure 18.18](#)). The total process of exchanging a segment of the GIL, including the recommissioning high-voltage testing, was finished in less than 1 week. The results demonstrate that the GIL can be repaired on site and then returned to service without any problems. The repair process requires only simple tools and is easily carried out in a short time.

Mixing of the gas was performed on site using a newly developed computer-controlled gas mixing device. The mixing process is continuous and arrives at a very high accuracy of the chosen gas mixture in the GIL. The gas mixture can be stored in standard high-pressure gas compartments (up to 200 bar) and can be reused after recommissioning.



FIGURE 18.17 Computer-controlled orbital welding on site. (Courtesy of Siemens.)



FIGURE 18.18 Cutting the enclosure pipe with a saw. (Courtesy of Siemens.)

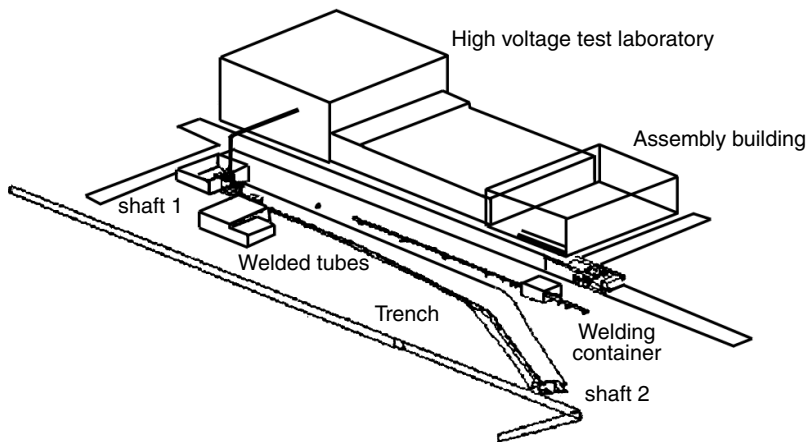


FIGURE 18.19 Site arrangements of the directly buried long-duration test. (Courtesy of Siemens.)

18.4.3.2 Long-Duration Test on a Directly Buried GIL

The long-duration test for the buried GIL was carried out on a 100-m-long test setup. Figure 18.19 shows the site arrangements. The laying procedure was carried out under realistic on-site conditions. Installation of the GIL under these conditions has proved the suitability of this laying procedure. The economy of the tools and procedures developed for this solution have been successfully demonstrated.

The tunnel-laid GIL described here is the first one with a N_2/SF_6 gas mixture to be tested and qualified in a long-duration test. The long-duration test — which involves extremely high stresses over a period of 2500 h (simulating a lifetime of more than 50 years) and a planned interruption to simulate a repair process — was concluded successfully. The results demonstrate once again the excellent performance and high reliability of the GIL [16, 17].

Figure 18.19 shows the IPH high-voltage test laboratory in Berlin with the high-voltage connection to shaft 1. From shaft 1, the trench with the directly buried GIL of 100-m length, including elastic bending and a directly buried angle module, proceeds to shaft 2 at the end. In shaft 2, a ground switch closes the current loop. The current-injection devices are in shaft 1. The shaft structures at the ends of the tunnel-laid GIL accommodate the separating modules and expansion fittings. The secondary equipment with the telecommunications system is also located there.

A crane transports the assembled GIL unit from the nearby assembly building to the welding container situated beside the trench, where the straight GIL segments are joined using an orbital-welding machine. The final on-site assembly takes place either beside the trench or in the shaft structures. The place of assembly depends on the civil engineering design dictated by local conditions. The installation finishes with the laying of the GIL in its final position. Figure 18.20 shows the trench-laying of the GIL with cranes. The trench follows a spherical curve with a bending radius of 400 m, which can be seen in Figure 18.20.

The process of constructing the trench and laying the GIL is quick and cost effective. The thermal expansion of the enclosure is absorbed by the surrounding bedding of coarse material by means of frictional forces. The bedding must also have sufficient thermal conductivity to dissipate the heat losses from the GIL. The temperature at the transition from the enclosure to the ground does not exceed 50°C when 2250 MVA are transmitted continuously by the GIL.

For the purpose of commissioning, comprehensive electrical and mechanical tests are necessary to verify the properties of the directly buried GIL. In addition to verifying the dielectric properties and checking the secondary equipment, the tests listed in Table 18.7 must be performed.

In addition, the typical elements of the secondary equipment of the GIL were employed: thus, partial discharge (PD) measurement was carried out during commissioning and on-line during the test. The gas properties, such as temperature and pressure, were monitored on a continuous basis. Arc-location



FIGURE 18.20 Trench of 55-m-long section during laying and view into the trench. (Courtesy of Siemens.)

sensors were implemented. Radio sensors measured conductor temperature, gas density at the conductor, and the enclosure temperature in the ground at several points. The mechanical behavior of the GIL was studied by monitoring data from displacement sensors in the shaft structures and along the route. These sensors record the movement of the GIL relative to the ground or to the building.

During the course of the long-term test, the essential physical variables that describe the GIL — and that are used to prove the parameters of the calculations — are recorded. In addition to the electrical stress imposed on the system by voltage and current, the above-mentioned temperatures and movement were recorded.

TABLE 18.7 Tests on Commissioning and Recommissioning

Pressure test	Verification per pressure-vessel regulation
Gas-tightness test	Checking of flange joints
State of gas mixture	Mixture ratio
	Filling pressure
	Dew point
Corrosion-protection-coating voltage test	10 kV/min
Resistance test	Main circuit

Source: Courtesy of Siemens.

18.4.3.3 Results of the Long-Duration Testing

18.4.3.3.1 Thermal Aspects

The GIL and its surrounding soil is a system of thermally coupled bodies, with inner heat produced by circulation of electrical current in both the conductor and the enclosure. Convection and radiation remove the heat losses from the conductor to the enclosure, while heat transfer in the annulus by conduction is negligible. This heat, adding to the losses by Joule effect from the enclosure, dissipates in the soil mainly in the radial direction to the surface of the soil and then flows into the ambient air by convection. The soil parameters were obtained from various literature sources documenting the soil properties in Berlin.

Before performing the unsteady-state study of the thermal behavior of the GIL, a steady-state model was developed taking into account the mechanisms of conduction in a solid body, natural convection in a cylindrical cavity, and radiation and convection in the interface between the soil surface and the air. The thermal system was divided into two parts — the GIL and the surrounding soil — and the physical phenomena occurring in each part was modeled. The FEM method (ANSYS program) was used first to check the accuracy of the developed analytical model and then to carry out the unsteady-state analyses of the thermal behavior of the buried GIL.

18.4.3.3.1.1 Calculation Model — Calculations were carried out using the finite element method. Heat loss, heat-transfer coefficient, and thermal resistance in the annular gap between the conductor and enclosing tube were calculated using a steady-state method according to the IEC 60287 standard [18]. These results were then used as constants in the transient calculation.

Calculations for the GIL cross section at the first location were carried out with the following parameters:

Cover $h = 0.7$ m ($h = 2.6$ m for the second location)

Thermal conductivity, $\lambda = 1.6$ W/mK

Soil temperature, $T_s = 15^\circ\text{C}$

Initial values for soil temperature, $T_i = 20^\circ\text{C}$

The thermal resistance of the soil was measured at the start of the test at three different places (at the ends of the line and in the center). At each of these points, measurements were taken at two depths between 0.9 and 2.3 m. The average thermal resistance measured varied from 0.46 to 0.80 mK/W, a 70% difference between the extreme measured values. The measurements show a wide scatter from the mean value. The thermal resistance that was used in the calculations was taken as the mean values of the measurements.

The boundary conditions used in the calculations were as follows:

Interface between soil and air: heat-transfer coefficient 20 W/m²K

Air temperature is taken as an approximation of the measured air temperature by a sine function

Temperature of soil: 15°C (20 m away from the GIL)

Initial temperature of soil: 20°C

Bisecting line: heat loss 0 W/m² (symmetry conditions)

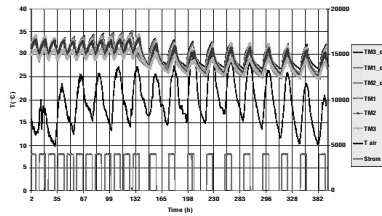


FIGURE 18.21 Comparison of numerical and experimental results of overload current rating of a directly buried GIL long-duration test, short and long cycle. (Courtesy of Siemens.)

Calculations were carried out for the following cycles load:

Short cycle

8 h, $I = 4000$ A, loss = 145 W/m

4 h, $I = 0$ A, loss = 0 W/m

Long cycle

8 h, $I = 4000$ A, loss = 145 W/m

16 h, $I = 0$ A, loss = 0 W/m

18.4.3.3.1.2 Comparison of Calculations and the Test Results — In order to compare the measured temperatures with the calculated temperatures, heating of the GIL during the whole test time was simulated. Comparisons of the measured and the calculated temperatures for a 1-m depth and 16 days (01.09.99 to 16.09.99), with two cycles occurring above, below, and to the side of the enclosing tube. The calculations agree well with the measured values. The maximum temperatures rose slowly during the short cycles and reached 35°C after 8 days. During the second period, the cooling phase was extended from 4 h to 16 h, which was why the temperatures in the GIL system fell (Figure 18.21). In this case, the maximum enclosing-tube temperatures were less than 33°C.

The calculations, unlike the measurements, show that the maximum temperature is to be found around the circumference of the underside of the enclosing tube, since the effect of heat transfer by natural convection from the inner conductor to the enclosing tube is not taken into account in the calculations. In the upper and lower parts of the enclosing tube, the different temperatures can be explained by variations in the resistance of the soil.

The diagram in Figure 18.22 shows the temperature distribution of the calculations in the soil at time 188 h (7.8 days) during the heating phase. The temperature measured during the test is assumed as a marginal condition for the air temperature. Temperature distributions during the day and the night show a difference only in the higher layer of soil immediately below the ground surface. This can be explained by the heat transmission between air and the surface of the ground due to the lower air temperature during the night. Heat transmission from the GIL is better at night, since the temperatures in the soil are slightly lower. The fluctuation in air temperature between night and day did not have as great an influence on the temperature distribution in the GIL and the soil as those that caused the load variation.

Further simulations of the test were carried out for a depth of 2.9 m during the same period as above (01.09.99 to 16.09.99). A comparison of calculations and measurements showed good agreement between the calculations and the measurements.

The calculations show that the temperatures at the bottom and the top are higher than the temperature at the sides, and the temperature difference is less than 2°C. The temperature at the bottom is slightly higher than the temperature at the top ($\Delta T \leq 0.5^\circ\text{C}$). In contrast to this, the test showed a considerable temperature difference between the bottom, the top, and the sides, with a high value at the top and a low value at the bottom. In this example, the temperature at the circumference of the pipe is not constant because the not-unsteady effect of the natural convection between the inner conductor and the enclosing tube was included in the calculation.

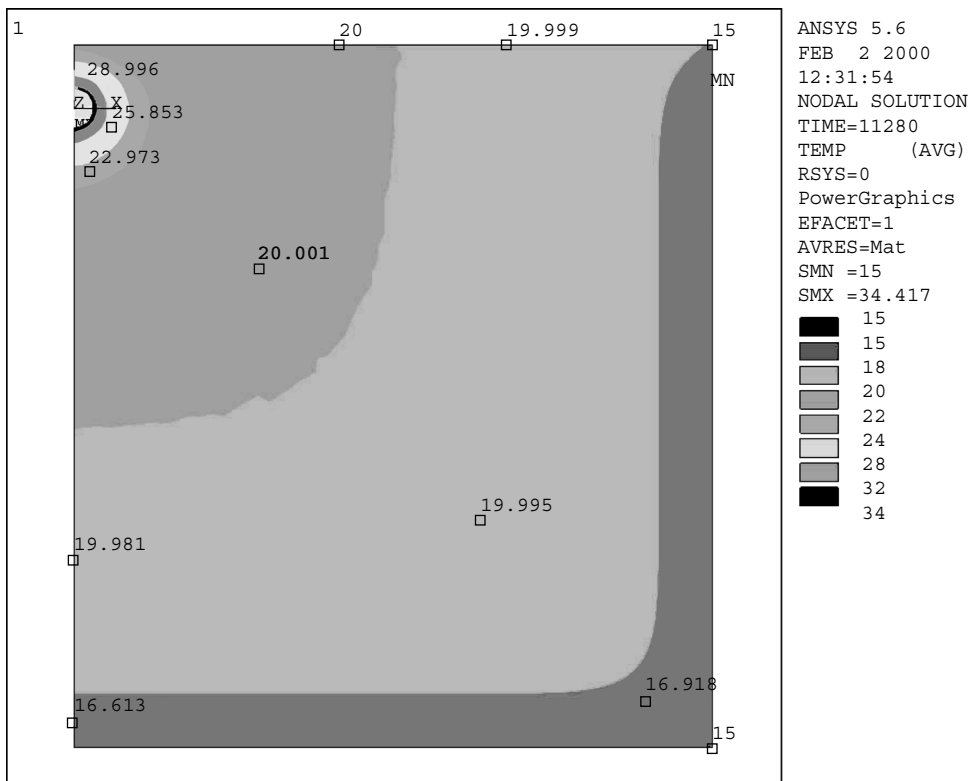


FIGURE 18.22 Temperature distribution at time $t = 188$ hours and at depth 1.2 m, heating phase. (Courtesy of Siemens.)

18.4.3.3.2 Mechanical Aspects

At measurement points in the middle of the right section on the buried GIL, only very minor movements were recorded. The measured values vary between -1.1 and 0 mm. This corresponds to the maximum absolute movement of the long section of pipe near the bend enclosure in the direction of shaft 1, which connected to the longest section (Figure 18.19). The two sections of pipe can be regarded as an adhesion zone.

A measurement point in the shaft at the end of the test section measures the movement of the expansion joint and at the same time corresponds to the change in the pipe. Measurements of the pipe movements are shown in Figure 18.23. The enclosing-tube temperatures at the first cross section at a distance of about 9 m from the shaft vary on average between 28 and 34°C in the case of the short cycles ($\Delta T = 6^{\circ}\text{C}$) and between 25 and 33°C in the case of the long cycles ($\Delta T = 8^{\circ}\text{C}$). During this period, the enclosing tube in the shaft moved from -3.4 to $+0.8$ mm, which corresponds to an absolute distance of $\Delta l = 4.2$ mm.

18.5 Advantages of GIL

The GIL is a system for the transmission of electricity at high power ratings over long distances. Current ratings of up to 4000 A per system and distances of several kilometers are possible in tunnel-laid or directly buried GILs. As a gas-insulated system, the GIL has the advantage of electrical behavior similar to that of an overhead line, which is important to the operation. Furthermore, the gases do not age, so there is almost no limitation in lifetime, which is a huge cost advantage given the high investment costs of underground power transmission systems.

TABLE 18.8 GIL Movement in Long-Duration Tests

	Movement (mm)	Absolute Distance (mm)
Pt 2	−0.6/−0.4	0.2
Pt 3	−0.5/−0.3	0.2
Pt 4	−0.1/0	0.1
Pt 5	−1.1/−0.6	0.5

Source: Courtesy of Siemens.

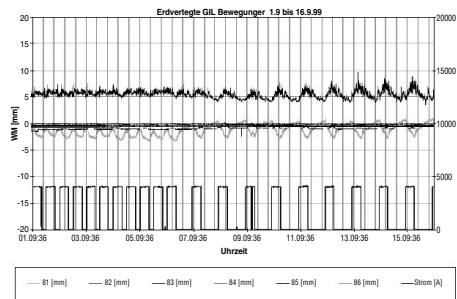


FIGURE 18.23 Mechanical aspects, movements of the enclosing tube during long-term testing of the directly buried GIL. (Courtesy of Siemens.)

Because of the large cross section of the conductor, the GIL has the lowest electrical losses of all available transmission systems, including overhead lines and cables. This reduces operating costs while reducing the utility’s contribution to global warming, since less power needs to be generated.

Personnel safety in the presence of a GIL is very high because the metallic enclosure provides reliable protection. Even in the rare case of an internal failure, the metallic enclosure is strong enough to withstand the stress of failure. The inherent safety of the GIL system, which contains no flammable materials, makes it suitable for use in street or railway tunnels and on bridges. The use of existing tunnels has obvious economic advantages by sharing the costs and can solve some environmental problems because no additional overhead line is needed. Because of the low capacitive load of the GIL, long lengths of 100 km and more can be built.

The GIL is a viable and available technical solution to bring the power transmitted by overhead lines underground, without reducing power-transmission capacity, in cases where overhead lines are not possible.

18.5.1 Safety and Gas Handling

The GIL is a gas-filled, high-voltage system. The gases used, SF₆ and N₂, are inert and nontoxic. The 7-bar filling pressure of the GIL is relatively low. The metallic enclosure is solidly grounded and, because of the wall thickness of the outer enclosure, offers a high level of personal safety. The mechanized orbital-welding process ensures that the connections of the GIL segments are gastight for the system’s lifetime.

Even in case of an internal failure, which is very unlikely, the metallic encapsulation withstands the internal arc so that no damage is inflicted on the surroundings. In arc fault tests in a laboratory, it was proven that no burn-through occurs with fault currents up to 63 kA, and the increase of internal pressure during an arc fault is very low. Even under an arc fault condition, no insulating gas is released into the atmosphere.

For the gas handling of the N₂/SF₆ gas mixture, devices are available for emptying, separating, storing, and filling the N₂/SF₆ gas mixtures. Figure 18.24 shows the closed circuit of the insulation gas with all devices used for gas handling. The initial filling is done by mixing SF₆ and N₂ in the gas mixing device

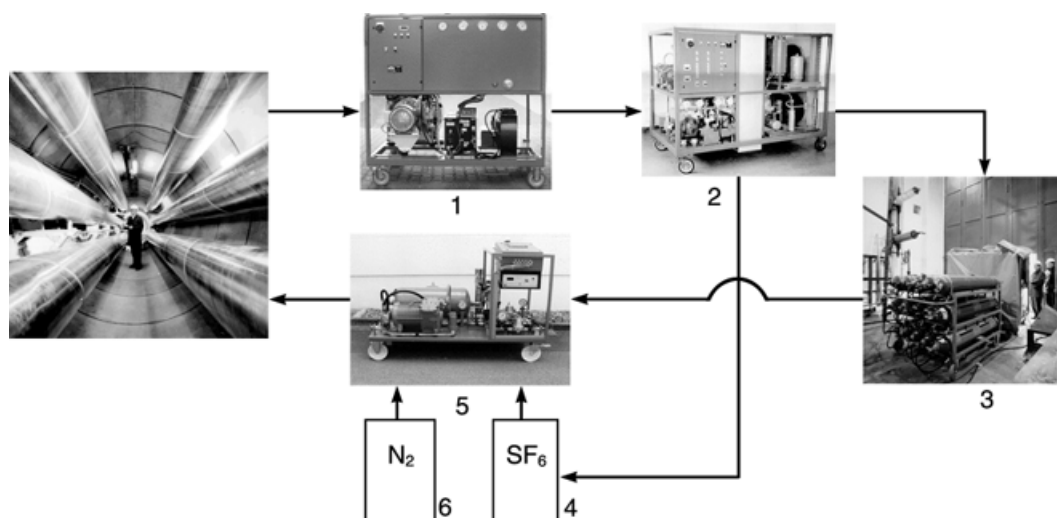


FIGURE 18.24 Gas-handling devices. (Courtesy of Siemens.)

(5) in the required gas mixture ratio. The initial filling is normally sufficient for the whole lifetime of the GIL because of the system's high gastightness. For emptying the GIL system, the gas is pumped out with a vacuum pump (1), filtered, and then separated (2) into pure SF_6 and a remaining gas mixture of N_2/SF_6 . This N_2/SF_6 gas mixture has an SF_6 content of only a few percent (1 to 5%), so it can be stored under high pressure up to 200 bar in standard steel bottles (3). Three sets of steel bottles can hold the gas content of a 1-km section for storage. The pure SF_6 is stored (4) in liquid state. To fill or refill the GIL system, a gas mixing device (5) is used, including a continuous gas monitoring system for temperature, humidity, SF_6 percentage, and gas flow. The gas mixing device has input connections for pure N_2 (6), pure SF_6 (4), and gas mixtures containing a low percentage of SF_6 . The mixing device adjusts the required N_2/SF_6 gas percentage used in the GIL, e.g., 80% N_2 .

With these gas-handling devices, a complete cycle of use and reuse of the gas mixture is available. In normal use, the SF_6 and N_2 will not be separated completely because the gas mixture will be reused again. A complete separation into pure SF_6 , as used, e.g., in gas-insulated substations (GIS), can be done by the SF_6 manufacturers. Thus the requirements of IEC 60480 [11] and IEC 61634 [3] are fulfilled.

18.5.2 Magnetic Fields

18.5.2.1 General Remarks

Magnetic fields can disturb electronic equipment. Devices such as computer monitors can be influenced by magnetic-field inductions of $\geq 2 \mu\text{T}$. Furthermore, magnetic fields may also harm biological systems, including human beings, a subject of public discussion. A recommendation of the International Radiation Protection Association (IRPA) states a maximum exposure figure for human organisms of $100 \mu\text{T}$. In Germany, this value has been a legal requirement since 1997 [19].

Several countries have recently reduced this limit for power-frequency magnetic fields. In Europe, Switzerland and Italy were the first to establish much lower values. In Switzerland, the maximum magnetic induction for the erection of new systems must be below $1 \mu\text{T}$ in buildings, according to NISV [20]. Today some exceptions may be accepted. In Italy, $0.5 \mu\text{T}$ has been proposed for residential areas in some regions, with the goal of allowing a maximum of $0.2 \mu\text{T}$ for the erection of new systems. This trend suggests that, in the future, electrical power transmission systems with low magnetic fields will become increasingly important.

The GIL uses a solid grounded earthing system, so the return current over the enclosure is almost as high as the current of the conductor. Therefore, the resulting magnetic field outside the GIL is very low.

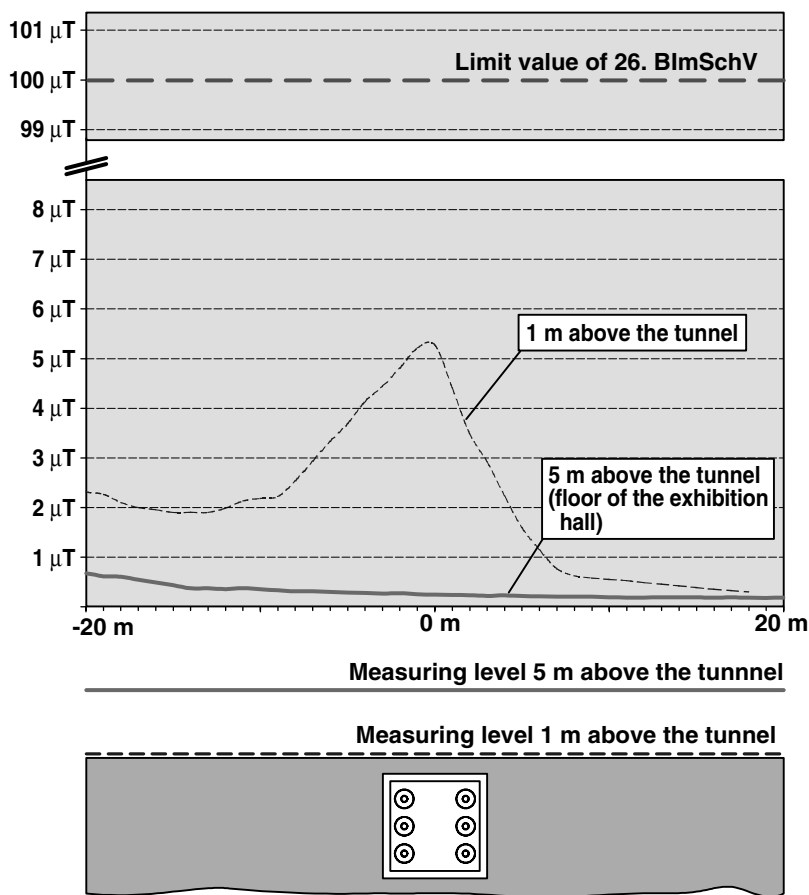


FIGURE 18.25 Measured values of the magnetic induction above the GIL tunnel at PALEXPO, Geneva, at a rated current of 2×1000 A. (Courtesy of Siemens.)

The installation at PALEXPO in Geneva demonstrates that GILs can fulfill the high future requirements that must be expected in European legislation.

18.5.2.2 Measurements of the Magnetic Field at PALEXPO, Geneva

The measurements at PALEXPO in Geneva were carried out with both GIL systems under operation with a current of 2×190 A. Based on the measured values, the magnetic induction was calculated for the load of 2×1000 A. Inside the tunnel between the two GIL systems, the maximum magnetic induction amounts to $50 \mu\text{T}$.

The magnetic field at right angles to the GIL tunnel is presented in Figure 18.25. The measurements were taken at 1 m and 5 m above the tunnel, which is equivalent to the street level and to the floor of the PALEXPO exhibition hall. The magnetic induction on the floor of the fair building is relevant for fulfilling the Swiss regulations for continuous exposure to magnetic fields. The 1-m maximum value amounts to $5.2 \mu\text{T}$ above the center of the tunnel. The maximum induction at 5 m above the tunnel is $0.25 \mu\text{T}$. This result is only 0.25% of the permissible German limit [12] and 25% of the new Swiss limit [20].

It is worth mentioning that cross-bonded high-voltage cable systems need to be laid at a depth of 30 m or more to achieve comparable induction values. There is a range of possibilities for reducing the magnetic field in cable systems, such as ferromagnetic shielding, compensation wires, or laying in steel tubes. All these measures, however, increase the losses markedly. Table 18.9 provides a comparison of different 400-kV transmission systems.

TABLE 18.9 Comparison of Different 400-kV Transmission Systems

	VPE cable 2XS(FL)2Y ^a 1 × 2500, cross bonding	Overhead line 4 × 240/40 Al/St	GIL ^a 520/180
Rated voltage (kV)	400	400	400
Thermal limit load (MVA)	1080	1790	1790
Overload (60 min)	1.2 times	1.2 times	1.5 times
Reactive power compensation	Needed	Not needed	Not needed
Max. induction in (μT) at 2 × 1000 MVA at ground level	29	23.5	1.4
Thermal system losses ^b at 1000 MVA (W/m)	71	194	43
External influences (environment, animals)	No	Yes	No
Behavior in case of fire	Fire load with plastic	No additional fire load	No additional fire load
Damage to neighboring phases in event of failure	Possible	Possible	Not possible
Maintenance	Maintenance free ^c	Needed	Maintenance free ^c

^a Tunnel laid, natural cooling, level above ground = 2 m.

^b Conductor temperature = 20°C.

^c Corrosion-protection test is required only for direct burial.

Source: Courtesy of Siemens.

A comparison of calculations and measurements made at PALEXPO shows that it is not sufficient to focus on the GIL only. The current distribution through the grounding systems around the GIL also has a significant influence. Along the overhead line, a current is induced into the ground wire and then conducted through the enclosure of the GIL. The increase in the magnetic field at a distance of 20 m from the GIL (Figure 18.25) is related to induced currents in the ground grid.

The magnetic inductions above the GIL trench are negligible and meet the Swiss requirements under full-load conditions. However, the results show that the magnetic fields induced by the grounding system also need to be considered in the system design. All measured and calculated values of the induction from the GIL are far smaller than those for comparable overhead lines and conventional cable systems.

18.6 Application of Second-Generation GIL

The first application of the second-generation of GIL was implemented between September and December 2000. After only 3 months erection time, the overhead line was brought underground into a tunnel (Figure 18.27). In January 2001 the line was energized again.

Figure 18.26 shows the delivery of GIL transport units to the preassembly area. The preassembly tent was placed directly under the overhead line and above the shaft connected to the tunnel right under the street. The space was limited because of an airport access road on one side and the highway to France on the other side. Nevertheless, the laying proceeded smoothly. The positive experience from this project shows that even GIL links for long distances can be installed within a reasonable time. The highly automated laying process has proved to guarantee a consistent quality on a very high level over the complete laying process, and the commissioning of the system was carried out without any failures.

During erection of the GIL, a preassembly tent was placed directly above the access shaft connected to the tunnel near Pylon 175 (Figure 18.27). The narrow space between an airport access road on one side and the highway A1 to France on the other side necessitated use of the space directly under the existing overhead line for the site work. A total of 162 pieces of straight GIL units, each 14 m long, were preassembled, brought into the tunnel, welded together, and continuously pulled toward the end of the tunnel at Pylon 176. Thanks to advanced site experience, it was possible to double productivity for assembly of the GIL sections from two connections per shift per day to four.



FIGURE 18.26 Delivery of transport unit to the preassembly area. (Courtesy of Siemens.)

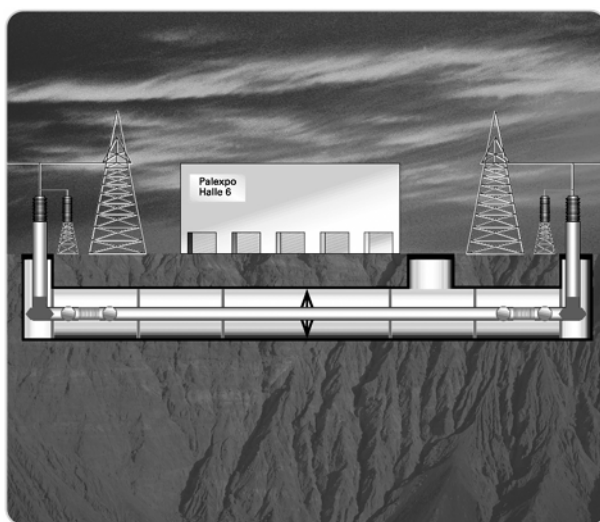


FIGURE 18.27 Principle of the PALEXPO project. (Courtesy of Siemens.)

Erection of the PALEXPO GIL started in September 2000 and was completed within 3 months. The double-circuit overhead line was brought underground into a square tunnel (Figure 18.8). The elastic bending of the GIL aluminum alloy tubes (minimum bending radius of 400 m) was sufficient to follow the layout of the tunnel route.

The technical data for the PALEXPO GIL are shown in Table 18.10. The power transmission capacity of the tunnel-laid GIL allows the maximum power of an overhead line to continue underground without any power transmission reduction. Surge arresters are used at the GIL terminations.

For monitoring and control of the GIL, secondary equipment is installed to measure the gas density. An electrical measurement system is used to detect arc location. Very fast transient electrical signals are measured at the ends of the GIL, and the position of a very unlikely internal fault can be calculated with an accuracy of ± 25 m.

TABLE 18.10 Technical Data for the PALEXPO GIL

Type	Design	Project
Nominal voltage (kV)	420	300
Nominal current (A)	3150/4000	2000
Lightning impulse volt (kV)	1425	1050
Switching impulse volt (kV)	1050	850
Power frequency volt (kV)	650	460
Rated short-time current (kA/3 s)	63	50
Rated gas pressure (bar)	7	7
Insulating gas mixture	80% N ₂ , 20% SF ₆	80% N ₂ , 20% SF ₆

Source: Courtesy of Siemens.

Given the importance of this high-voltage line for the power system — and despite the security constraints for the construction site — the operator endeavored to keep the line in service during the whole construction period. Operation of the link was suspended only for a span of 3 weeks during the GIL commissioning tests and connection.

18.7 Quality Control and Diagnostic Tools

In the complex insulation system of a real GIL, the intrinsic dielectric strength of N₂/SF₆ mixtures — presented in Section 4.1 by the pressure-reduced critical field — is affected by many factors. The usual surface roughness of metal surfaces is well understood in gas-insulated systems [21]. Metal protrusions or mobile particles are also studied in many cases, and their influence is also well understood [22].

The statistical distribution of breakdown voltage in gas mixtures was found to be similar to that of pure SF₆ of equal dielectric strength [23]. Therefore, the approved conventional test procedures for GIS can be applied to confirm the required withstand levels [21]. For insulation coordination (to make the correct choice of high voltage and best voltages for type testing) of extended transmission lines, the Weibull distribution has to be applied because of the statistical distribution of the flashover voltage levels [24]. Thus the knowledge and experience of more than 25 years of GIS installations and operation can be fully applied to GIL installations because GIS and GIL show the same statistical behavior for high voltage flashovers.

With careful assembly and efficient quality control, defects are practically ruled out. Mobile particles are the most common defect, and these are usually eliminated by conditioning procedures during power-frequency high-voltage testing [8]. In a conventional GIS with a complex insulation system, particles are moved by a stepwise increased ac field stress into low-field regions that act as natural particle traps. However, there are no such natural particle traps in the plain insulation system of a GIL. Therefore it has been equipped with artificial particle traps all along the GIL extension, and these traps have proved to be very efficient.

Modern diagnostics are applied for the detection, localization, and identification of defects. The VHF method proved to be most efficient [8]. Its application is restricted by signal attenuation and the correspondingly limited measuring range of installed sensors. In a GIS, this attenuation is mainly caused by the conical spacers that are usually installed. The maximum distance between sensors should therefore normally not exceed 20 m. In a GIL, an efficient VHF PD measurement can be carried out even with distances between sensors of several hundred meters. This enables use of the UHF method in a GIL, as successfully performed for the first time on site in Geneva [9].

Moisture penetration by diffusion through the enclosure and from the bulk of the insulators into the gas occurs much less frequently in a GIL than in a conventional GIS because of the excellent gastightness and the low amount of solid insulating material. The insulation quality of the insulator surfaces can therefore reliably be preserved by conventional measures to avoid dewy surfaces of reduced dielectric strength.

Altogether, it can be expected that the GIL will give the same or even better long-term performance than a GIS, which demonstrates a long service lifetime with no critical aging even after 30 years of operation [25]. The GIL uses almost the same materials, while the amount of solid insulating material and SF₆ is considerably reduced. Moreover, the requisite quality control can be obtained by means of tests and modern diagnostics. In conclusion, it can be said that the on-site high-voltage quality control and the diagnostic tools used have proved to be very successful. The GIL in Geneva went into service without problem.

18.8 Corrosion Protection

For applications where aluminum pipes are used in air aboveground or in a tunnel, aluminum generates an oxide layer that protects the enclosure from any kind of corrosion. The oxide layer of an aluminum pipe is very thin, only a fraction of a micrometer, but it is very hard and very resistive against a gaseous environment like the atmosphere. In most cases it is not necessary, even in outdoor applications, to protect the aluminum pipes against corrosion with, e.g., coloring.

Going underground for directly buried systems, the situation regarding corrosion changes, and a corrosion protection is required. Two basic methods are used today: a passive corrosion protection and an active corrosion protection. The passive corrosion protection is an added layer of noncorrosive materials, e.g., polyethylene (PE) or polypropylene (PP), while the active protection system uses voltage protection to direct corrosion from the protective aluminum enclosure toward a loss electrode.

18.8.1 Passive Corrosion Protection

Passive corrosion protection is used widely for all kinds of metallic underground systems that have direct contact with the soil, e.g., electric power cables, oil or gas pipelines, and all kinds of other pipes.

There are several different technologies available on the market to add a coating to a pipe as a passive corrosion protection. In all cases, the processes used and the materials are similar. The surface of the metallic aluminum enclosure needs to be degreased, and the oxide layer needs to be removed. Acid fluids or mechanical brushes can be used to accomplish this. In some cases, both of them are used. If fluids are used to prepare the enclosure for the coating process, the pipe is run through a curtain of fluid acid. If mechanical treatment is used, then brushes treat the surface accordingly, sometimes together with a fluid. These processes are the same for steel and aluminum pipes and are run with the same machines. After the surface of the aluminum pipe is prepared, a first layer of a corrosion-protection fluid is brought onto the pipe to stop corrosion. This first layer is the active part of the passive corrosion protection and is only a few micrometers thick. On top of this layer, a 3- to 5-mm layer is added mainly for mechanical protection reasons. For this protective layer, two basic processes are applied: the extruded-layer and the tape-wrapped-layer methods. The use of these passive corrosion-protection methods has a long history and thousands of kilometers of experience as well as years of operating experience.

Figure 18.28 shows a GIL with passive corrosion protection. In the middle of the photo the blank aluminum enclosure is shown, prepared for the welding process. To the right and left of the blank, the small dark bands are the active corrosion protection layer. Finally, to the far right and left, is the white cover for mechanical protection, which is a PE or PP coating 3 to 5 mm thick.

After the pipe segments are welded together, it is also necessary to protect the welded area. There are various corrosion-protection processes available that can be applied on site. Figure 18.29 shows how one such on-site corrosion-protection method is applied. In this case, a corrosion-protection system based on a shrinking method is used. Other methods involve granulates or tapes and are also widely used in the pipeline industry.

18.8.2 Active Corrosion Protection

With an active corrosion-protection method, the induced current generates a voltage potential of the metallic enclosure toward the soil. If this voltage level is at a potential of around 1 V toward a loss



FIGURE 18.28 GIL with passive corrosion protection. Center of photo: blank aluminum surface prepared for welding; dark bands on either side of aluminum surface: active corrosion protection layer (thickness of several micrometers); far left and right of photo: white surface providing mechanical protection (3 to 5 mm of PE or PP coating). (Courtesy of Siemens.)

electrode, then the loss electrode corrodes instead of the aluminum enclosure. The active corrosion-protection system is a backup to the passive corrosion-protection system. It is installed as an additional quality insurance system if the passive corrosion protection fails. Failures in the passive corrosion protection can occur over the lifetime of the system by outer damage through other earthworks or by cracks or voids in the protective material. If necessary, the active corrosion-protection system prevents corrosion in the event of cracks and voids in the passive corrosion-protection system.

Experience with installed, directly buried pipe systems worldwide shows that, over the decades, some cracks or voids in the passive corrosion-protection system can occur, which increases the induced current of the active protection system. The positive effect of the active corrosion-protection system is that each passive corrosion-protection failure need not be repaired immediately, and a guaranteed lifetime of the passive corrosion-protection system of 50 years can be extended by many more years. Repairs of passive corrosion-protection systems can be planned and concentrated on troublesome segments. Experience with oil and gas pipelines shows that the lifetime can be extended significantly without opening the pipe.

The active corrosion-protection system, also called cathodic corrosion protection, uses an induced current to adjust the protective voltage of approximately 1 V against the lost electrode. To reach this 1-V protective voltage, an induced current of approximately 100 μA is needed. The induced current is related to the total of the surface to be protected and increases with the length of the system and the numbers of failures. In practice, several kilometers can be protected with only one dc-voltage source because the current is low.

To obtain cathodic protection, the buried GIL must be a nonearthed system, which means that it must be insulated toward the ground potential. To allow the 1-V protection potential, the ground system is coupled with the GIL through a decoupling element, which could be a battery or a diode. This battery or diode ensures that a protective voltage of about 1 V is applied to the aluminum shield. If an earth fault of the electric system occurs, the failure current is conducted to the ground potential through the diode or battery.

Active corrosion protection can be easily installed along with the electrical transmission system, with no interferences between electrical transmission and the corrosion-protection voltage potential. Such electrical transmission systems have been operating for many years with no failures reported. The high reliability observed for pipelines and cables also applies to GIL systems.



FIGURE 18.29 On-site corrosion protection of the welding area — shrinking method. (Courtesy of Siemens.)

18.9 Voltage Stress Coming from the Electric Power Net

18.9.1 Overvoltage Stresses

Two typical GIL applications are represented by the connection of 400-kV overhead lines to a GIL with a length of 1 km and 10 km. The overhead line is protected by two shielding wires along its full length. The height of the last three towers is about 65 m, and the maximum footing resistance for the towers is about $7.5 \, \Omega$.

18.9.2 Maximum Stresses by Lightning Strokes

Based on these configurations of the overhead lines and the lengths of their insulator strings, the following maximum stresses by lightning strokes were evaluated and used to calculate the maximum overvoltage stresses on the GIL:

- Remote stroke: 2000 kV and 2100 kV
- Nearby direct strokes: 35 kA and 18 kA
- Stroke to towers: 200 kA

18.9.3 Modes of Operation

The basic arrangement allows calculation of lightning strokes on the GIL for the following modes of operation:

- Transport:
 - Overhead line connected by the GILs of 1-km and 10-km length
 - Overvoltage stresses caused by lightning strokes to the overhead line
- Open end:
 - GILs of 1-km and 10-km length connected on one end to the open bay of a substation
 - Overvoltage stresses caused by lightning strokes to the overhead line

18.9.4 Application of External and Integrated Surge Arresters

To protect the GIL against high lightning and switching overvoltage stresses, external surge arresters located at the last towers of the overhead line, as well as encapsulated metal oxide surge arresters immediately connected to the GIL at certain locations (integrated surge arresters), can be applied. For 400-kV systems with an earth-fault factor of ≤ 1.4 , the special integrated surge arresters have the following characteristic data:

- Rated voltage, $U_r = 322$ kV
- Continuous operating voltage, $U_c = 255$ kV
- Residual voltage at 10 kA, $U_{10kA} = 740$ kV

External metal oxide surge arresters commonly used in German 400-kV systems — those with $U_r = 360$ kV, $U_c = 288$ kV, and $U_{10kA} = 864$ kV — were taken into account.

18.9.5 Results of Calculations

For each mode of operation, for both lengths of GIL, and for the different possibilities of surge-arrester application, the maximum overvoltage stresses (depending on the distance from the left-hand-side end of the GIL) have been calculated for all kinds of possible lightning strokes. In all cases, the maximum stresses are caused by nearby direct strokes to line conductors. For the various possibilities of surge-arrester application, the maximum lightning overvoltage stresses are listed in [Table 18.11](#) for the GIL of 1-km length and in [Table 18.12](#) for the GIL of 10-km length.

18.9.6 Insulation Coordination

At least up to a length of some tens of kilometers, lightning overvoltage stresses are decisive for the insulation coordination of a GIL, since stresses by switching overvoltages at those lengths will be much lower than on overhead lines because of their lower surge impedance (60Ω compared with 300Ω for an overhead line). The insulation coordination of a GIL of up to 10-km length considered here is therefore based on the maximum stresses by lightning overvoltages.

TABLE 18.11 Maximum Overvoltage Stresses Depending on Mode of Operation and Number of Surge-Arrester Sets for a GIL of 1-km Length

Mode of Operation	Number of Surge-Arrester Sets at:		Maximum Overvoltages (kV) Caused by Nearby Direct Strokes to:	
	GIL	Tower ¹	(35 kA)	(18 kA)
Transport	2	—	1013 kV	913 ^b
	2	2	952 kV	890
Open end	2	—	1066 kV	958 ^b
	2	2	989 kV	938 ^b

¹ Tower means last tower of overhead line before the GIL.

Source: Courtesy of Siemens.

TABLE 18.12 Maximum Overvoltage Stresses Depending on Mode of Operation and Number of Surge-Arrester Sets for a GIL of 10-km Length

Mode of Operation	Number of Surge-Arrester Sets at:		Maximum Overvoltages (kV) Caused by Nearby Direct Strokes to:	
	GIL	Tower ¹	(35 kA)	(18 kA)
Transport	2	—	996 kV	904 kV
	2	2	983 kV	890 kV
	4	—	867 kV	837 kV
	4	2	842 kV	829 kV
Open end	2	—	1048 kV	950 kV
	2	2	1035 kV	940 kV
	4	—	902 kV	883 kV
	4	2	893 kV	877 kV

¹ Tower means last tower of overhead line before the GIL.

Source: Courtesy of Siemens.

Given the large amount of experience already gained with design tests and on-site tests of huge gas-insulated substations (GIS), the following procedures are proposed for selecting test voltages for on-site tests on GIL sections of up to 1-km length and of type tests on a representative length of GIL:

18.9.6.1 On-Site Tests

On-site tests are designed to verify that the GIL is free of irregularities after laying and assembling. Taking into account the safety factor of $K_s = 1.15$ (according to IEC 60071-2), a withstand voltage of $U_w \geq 1.15 U_{LEmax}$ — with U_{LEmax} = maximum overvoltage stress from the calculations — should be verified by these tests.

18.9.6.2 Type Tests (Design Tests)

On the other hand, the on-site test voltage corresponds to 80% of the required rated lightning-withstand voltage, U_{rw} , when type testing a representative length of GIL. At these tests, single flashovers on self-restoring insulation are permitted according to the applicable IEC standard 61640.

18.10 Future Needs of High-Power Interconnections

18.10.1 Metropolitan Areas

Metropolitan areas worldwide are growing in load density, mainly at their centers. Demand for power has grown because of the construction of huge residential and tall office buildings with air conditioning and lots of electronic equipment, leading to increases in electric loads of up to 10% per year in metropolitan areas

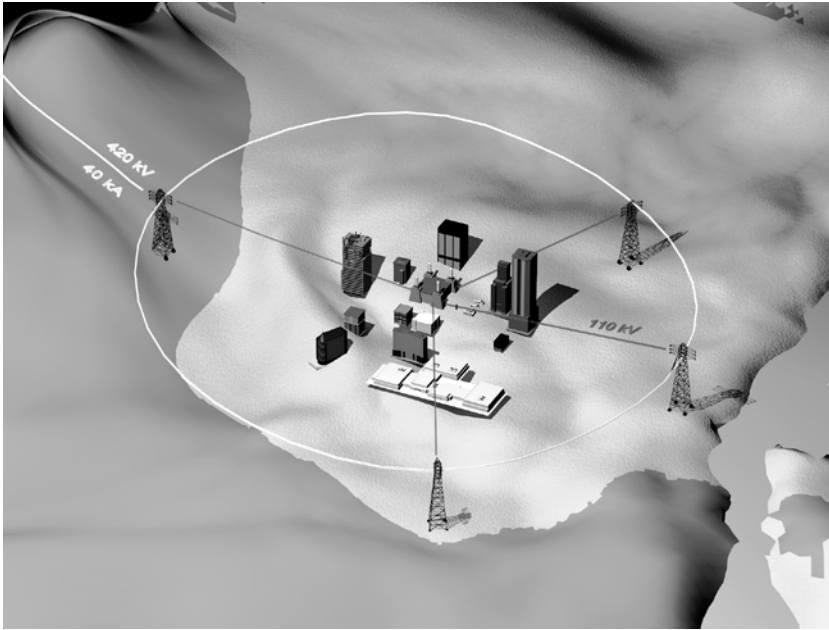


FIGURE 18.30 Power supply of metropolitan areas in 1970. (Courtesy of Siemens.)

[26]. The following short historical overview explains how the power supply of metropolitan areas has developed over the last 30 years.

Figure 18.30 shows the principle for power supply in a metropolitan area. Power generated in a rural area is connected to a metropolitan area by 420- or 550-kV overhead lines with a short-circuit rating of 40 kA. Several substations are placed around the city as overhead towers using a bypass or a ring structure around the metropolitan area, from which 110-kV cables transport electrical energy into the center of the city, where medium-voltage energy is distributed.

In [Figure 18.31](#), the metropolitan area has grown, with more tall buildings in the center. Most cities still have a 420/550-kV ring around the city, but the short-circuit rating has been increased to 50 kA or, in some places, to 63 kA. Note the second connection to the ring from another rural power generation area. More 110-kV cables are connected to the ring to transport the energy to the substations in the city for distribution. To increase the power transportation into the center of the city, it is not possible to increase the voltage to 1000 kV because of dielectric problems. Moreover, worldwide experience with very high short-circuit ratings shows that short-circuit rating values cannot go far above 63 kA because of mechanical problems. So the only way to increase the power transportation into the city is to lay 400-kV underground bulk-power-transmission systems right into the center. In such cases, the GIL offers the best solution.

[Figure 18.32](#) shows the metropolitan area as it may appear in 2010. The same metropolitan area with more buildings has grown further, and a 420/550-kV, 63-kA, double-system GIL was built as a diagonal connection underpassing the total metropolitan area. This GIL could have a length of 30 to 60 km. The solution illustrated here allows splitting of the short-circuit ratings of the ring into two half rings and to connect directly to the 400-kV high-transmission-power GIL in the center of the metropolitan area. The underground connection is a tunnel for GIL, as discussed in [Chapter 4](#), High-Voltage Switching Equipment.

18.10.2 Use of Traffic Tunnels

GILs can safely be routed through tunnels carrying traffic on rails or streets. This new application for electrical transmission systems with solid insulated cables was not possible until today because of the

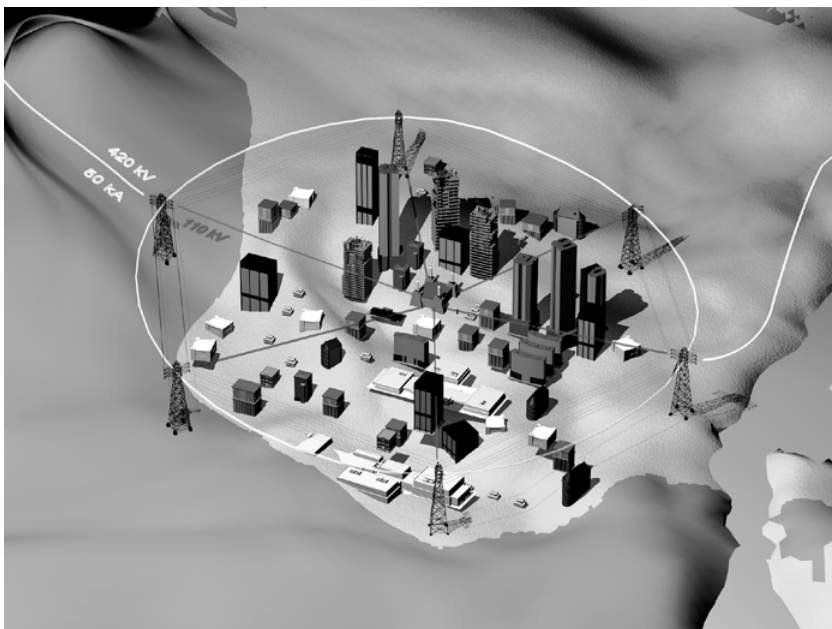


FIGURE 18.31 Power supply of metropolitan areas in 2000. (Courtesy of Siemens.)

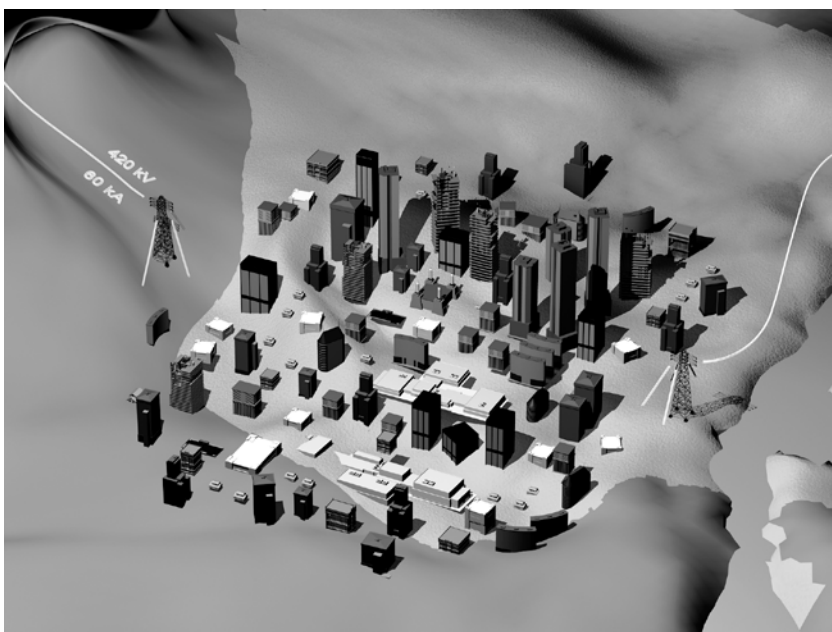


FIGURE 18.32 Power supply of metropolitan areas in 2010. (Courtesy of Siemens.)

risk of fire or explosion. The GIL has a solid metallic enclosure and does not burn or explode, as explained in [Chapter 4](#), High-Voltage Switching Equipment. The combinations of GIL and street or railroad tunnels are shown in [Figure 18.33](#). Three examples are given. The first one is a traffic tunnel with cars and a GIL mounted on top of the tunnel; the second is a double railroad tunnel system with a separate GIL tunnel; the third example is a double-track railroad tunnel with a GIL included.

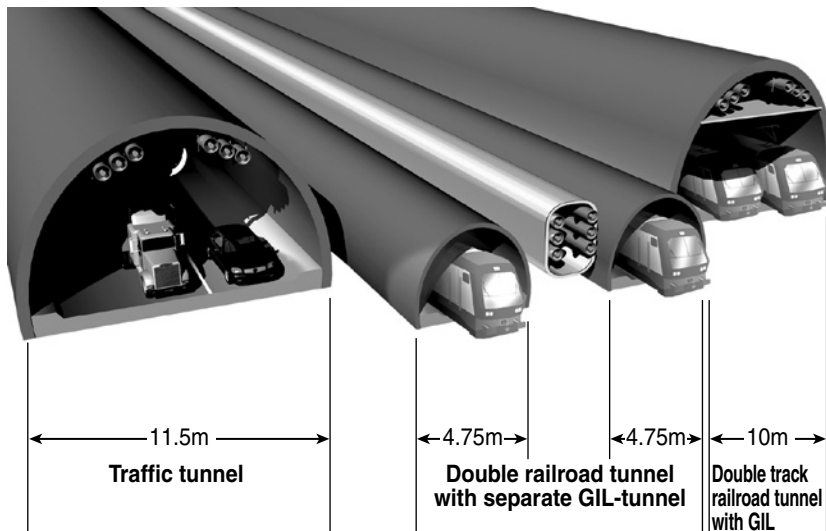


FIGURE 18.33 Different types of traffic tunnels to be used for GIL. (Courtesy of Siemens.)

The use of such traffic tunnels with GIL is now under investigation in different parts of the world. In the European Alps, interconnections between Germany, Austria, Switzerland, Italy, and France are now planned to improve the traffic flow and to allow trade of electric energy. In China and Indonesia, interconnections between the mainland and islands or between outlying islands are under investigation.

In the near future, GILs will become economically viable and will be widely used as high-power, long-distance transmission lines.

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